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ACCELERATION OF DISCHARGE PLASMA AND THE PRODUCTION OF STRONG SHOCK WAVES IN A CHAMBER WITH COAXIAL ELECTRODES

/ Following is the translation of an article by S. R. Kholev and D. S. Poltavchenko entitled "Uskoreniye Plazmy Razryada i Polucheniya Sil'nykh Udarnykh Voln v Kamere s Koaksial'nymi elektrodami" (English version above) in Doklady Akademii Nauk SSSR (Reports of the Academy of Sciences USSR), Vol. 131, No. 5, Moscow, 1960, pages 1060-1063. 7

(Presented by Academician Ya.B. Zel'dovich, 9 November 1959)

(Moscow State University imeni M. V. Lomonosov. Submitted 6 November 1959)

1. In a number of experimental studies ((1-8)etc.) diverse methods of accelerating a plasma while interacting with an electromagnetic field were investigated. The idea of the method of accelerating plasma examined below consists of the comparatively long (during the course, for example, of one or several current periods) interaction between a radial discharge current and a concentric magnetic field. The purpose of the study was to produce

strong shock waves as well, rather than merely to investigate the method of accelerating plasma. In this case a unique redistribution of energy may be realized: the gas, compressed by the accelerated plasma, can itself be converted to a plasma with an even higher temperature.

The accelerator was made in the form of two coaxial electrodes of cylindrical shape (Fig. 1 A): with the central core abc and tube def. Upon discharge of the capacitor bank C a current flows in the circuit, the direction of which is shown by arrows in Fig. 1 A. The radial discharge current I interacts with with the concentric magnetic field H of the central electrode. The pondermotive force F = IH produced as a result is always directed, independently of the direction of the current, toward the output away from the accelerating electrodes. In this manner, the magnetic field is made to act on the discharge plasma like a piston.

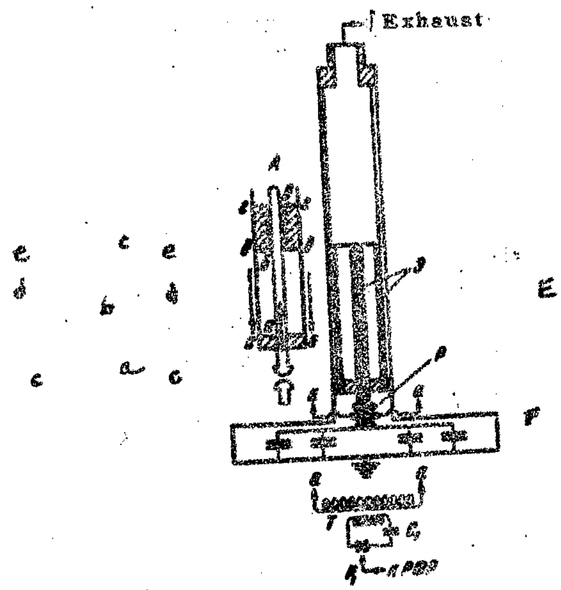

Fig. 1. E - accelerating electrodes; P and P_1 - dischargers; C_1 - initiating capacitor; T - pulse transformer; α - α - junction between the transformer and discharger P

Without finding out the concrete representation of the interaction between the magnetic field of the accelerating electrodes with the current flowing through

the gas, it is possible to determine the force acting on the plasma with increased inductance in the discharge circuit L with the simultaneous increase in the mass of the moving part of the circuit. In this case the equation of motion can be written:

$$\frac{d}{dt}(mv) = \frac{1}{2} I^2(t) \frac{dL}{dx}. \tag{1}$$

where m - is the mass of the accelerated gas (bcde in Fig. 1); v - is its velocity; dL/dx = b - the inductance of the accelerating electrodes incoming per unit length. The oscillogram of the discharge current can be approximated with good accuracy by the expression

$$I = Ae^{-Bt} \sin \omega t. \tag{2}$$

Constants A, B and the angular velocity ω are determined from the oscillogram.

Let

$$m = m_0 + kx, \tag{3}$$

where m_0 and k are constants. Then from (1) and (2), we have

$$\frac{d}{d\tau}\left[(m_0 + kx)\frac{dx}{d\tau}\right] = \frac{bA^2}{2\omega^2} e^{\alpha\tau} \sin^2 \tau, \tag{4}$$

where $\tau = \omega t$; $\alpha = -2B/\omega$. The integration of (4) with consideration of the initial conditions (x = 0, v = 0 when t = 0) gives:

$$(m_0 + kx)\frac{dx}{d\tau} = \varphi(\tau); \tag{5}$$

$$v = \omega \frac{dx}{d\tau} = \frac{\omega\varphi(\tau)}{\sqrt{m_0^2 + 2k\left[\int \varphi(\tau)\, d\tau - C\right]}}. \tag{6}$$

Here

$$\varphi(\tau) = \frac{A^2 b}{2\omega^3 (a^2 + 4)} \left[e^{a\tau} \left(a \sin^2 \tau - \sin 2\tau + \frac{2}{a} \right) - \frac{2}{a} \right];$$

$$C = \frac{A^2 b (3a^2 + 4)}{a^2 \omega^3 (a^2 + 4)^2}. \qquad (7)$$

(7)

2. Plexiglas cylindrical chambers with an inside diameter of from two to five centimeters and a length of from 50 to 90 cm were used in the experiments. The accelerating electrodes were made of brass, steel or duralumin. The battery capacity in different series of the experiments was 150, 600 and 2400 μf with an initial voltage of 5-6 kv. The manner of initiating the discharge is apparent from Fig. 1.

10 u sec

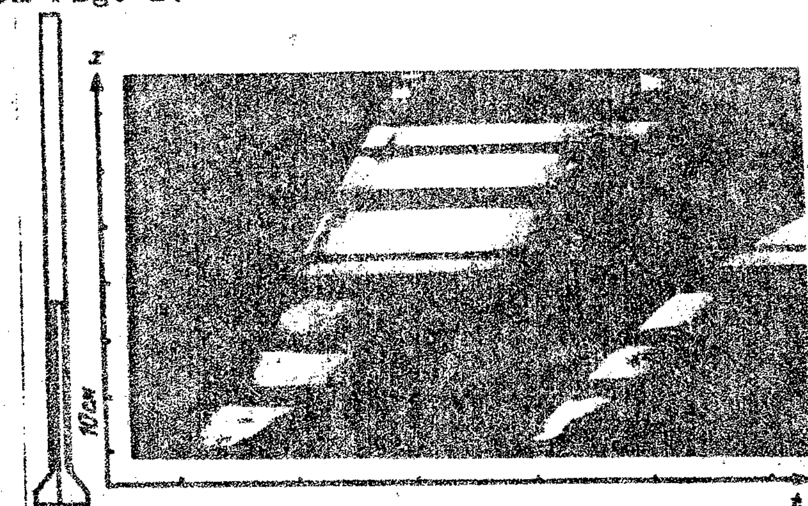

Fig. 2. V = 5 kv, C = 150 μf, D = 36.4 km/sec, p_1 = 0.08 mm Hg.

The experiments were conducted in air within the pressure range of 0.02 - 0.75 mm of mercury with continuous exhaust. The accuracy of measuring pressure was in the order of 10 percent. A photographic sequence of the distribution of the plasma in the chamber and measurement of velocity was taken with a SFR-2M photographic recorder. The error in measuring velocity was not over five percent.

To take oscillograms of the current the voltage with low inductive reactance ($1.5 \cdot 10^{-3}$ ohm, $1.5 \cdot 10^{-11}$ henries) occurring in the discharge circuit was put on an OK-17M oscillograph plate.

3. Figure 2 shows the typical development of self-luminosity of the process in a small chamber (2 cm diameter). Alongside the diagram of the chamber layout the acclerating electrodes are presented. Conical expansion at the lower part of the chamber was made to facilitate breakdown conditions at low pressures.

The most characteristic feature of development photos with the accelerating electrodes is the projection of discharge plasma out from the interelectrode area and its acceleration when moving between the electrodes. The experimental conditions are presented in the drawing. The leading front of the luminous flow in these conditions is a shock wave. The reason for such strong waves being produced (M =110 at the output of the accelerating electrodes) may be found in the accelerated motion of the

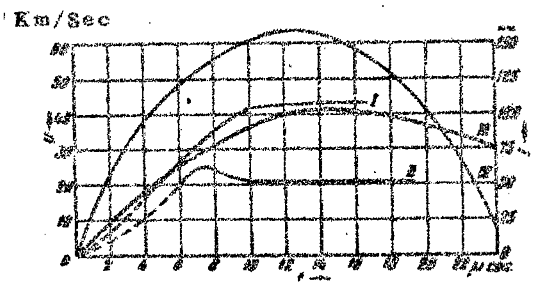

Fig. 3

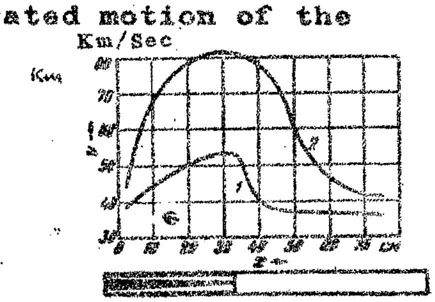

Fig. 4. V = 5 kv, C = 2400 µf, I = 560 ka.
1 -- p = 0.43 mm Hg.
2 -- p = 0.19 mm Hg.

discharge plasma, readily visible in the photos. The occurrence of a trailing edge of plasma is intrinsic. The acceleration of this trailing edge occurs apparently as a result of the existence of the strong magnetic field which acts on theplasma like a piston. Between 12 and 13 µsec. the current reaches its peak (~70 ka for the considered experiment), the magnitude of the magnetic field in the region behind the plasma is at this time ~20 kilogauss. The sharp acceleration of the trailing edge of the plasma at this time is excellently visible.

Fig. 3, 1 shows the effect of acceleration of the plasma in a 5 cm diameter chamber when C = 600 µf. The thick portions of curves I and III designate the period

movement of the shock front between the electrodes. Curve II represents the result of the experiment under the same conditions, although without the outside accelerating electrode (instead of this a ring was left at the base of the electrodes), when the described mechanism of accelerating the plasma did not operate. The dependence I (t) of phasing-in with the velocity curves is also shown for 5 kv (curve IV). Curve III was calculated according to formula(6) for the values of the constants determined from the current oscillograms: $A = 1.97 \cdot 10^5$ a, $o = - 0.139$, $w = 1.26 \cdot 105$ sec^{-1} and the known value $b = 3.4 \cdot 10^{-9}$ henries per centimeter. The constants m_0 and k which enter into this formula were determined in the following manner. Directly from equation (5) with a known value of velocity for the given moment of time the value of $m = m_0 + kx$ was determined. The moment of time was chosen in such a manner that the plasma was still moving between the electrodes, although the acceleration was equal to zero. This condition for the case shown in Fig. 3 is satisfied by point t = 10 usec (- = = 1.26). For this point ($d^2 x/dt^2 = 0$) we have from (4)

$$k = \frac{bA^2}{2v^2} e^{a\tau} \sin^2 \tau. \tag{8}$$

Knowing k and m from (3) we determine the value of the initial mass m_0. The constants determined in this fashion are equal in this particular case to: $m_0 = 2.2 \cdot 10^{-5}$ g, $k = 2.84 \cdot 10^{-5}$ g/cm. For comparison we will show that under these conditions (the initial pressure is 0.18 mm Hg.) the mass of the air which enters 1 cm (the order of width of the spark-over) of the length of the chamber (m_0) is equal to $2.16 \cdot 10^{-6}$ g. If one considers that the accelerated mass grows only due to gas passing through the shock front, then $k = 2.16 \cdot 10^{-6}$ g/cm. The higher figure for the experimentally determined values of m_0 and k is explainable, apparently, by the significant emission of matter from the electrodes (9).

In experiments with a battery of 2400 µf capacitors somewhat higher velocities were produced at comparatively great pressure. The results of these experiments are depicted in Figure 4. It is in place here to mention the significant acceleration of plasma as it moves between the accelerating electrodes together with marked attenuation after it issues from them.

Table 1

D, km/sec M p_1, mm Hg T_2, °K p_2, atm

D, км/сек	M	p_1, мм рт. ст.	T_2, °K	p_2, атм	ρ_2/ρ_1	n_e, см$^{-3}$
		I. C = 600 μф, V = 5 кв, l = 158 ка				
		A. With acceleration				
32	97,5	0,75	40 000	14	12,4	10^{17}
43	130	0,18	55 000	5,4	~13	~10^{16}
46	140	0,07	50 000	~2	~14	~10^{16}
49	148	0,02	~50 000	~1	~14—15	~10^{16}—10^{18}
55 (6 кв)	167	0,02	~55 000	~1	~14—15	~10^{15}—10^{16}
		B. Without acceleration				
20	61	0,70	25 000	5	13	$5 \cdot 10^{16}$
21	64	0,18	~25 000	~1	~14,5	~$6 \cdot 10^{15}$
28	85	0,03	~30 000	~1	~14	~10^{14}
		II. C = 2400 μф, V = 5 кв, l = 560 ка				
		With acceleration				
54	164	0,43	75 000	20	12	$2 \cdot 10^{17}$
82	248	0,19	130 000	19	~13	~10^{16}

Table 1 presents the equilibrium parameters of air behind the shock wave for certain typical experiments. D is the velocity of the front, the shock wave at the output of the accelerating electrodes; M is the Mach number, equal to D/α, where $\alpha = 0.33$ km/sec; p is the pressure; T -- temperature, ρ - density; the index 1 refers to the undisturbed gas, 2 - to the gas behind the shock front; n_e - is the concentration of electrons.

Calculation was done according to the measured velocity of the shock was at the output of the accelerating electrodes according to the data of work (10) for the conditions prevalent in our experiment. The symbol indicates that the given value has been determined with an accuracy of ± 50 percent. We underscore the fact that the problem of the equilibrium of the parameters of the

gas behind the shock wave has not yet been solved in our conditions and the data given in Table 1 are presented only for an estimate.

4. Consequently, the experimental results have confirmed the effectiveness of the proposed method of accelerating plasma. The velocities of the shock waves and plasma increased 1.5-2 times over those attained in conditions without accelerating coaxial electrodes and reached 30-80 km/sec at initial pressures of 0.7-0.02 mm of mercury of air and an initial voltage of 5 kv. It should notwithstanding be noted that hydrodynamic forces, as this has become evident from the experiments without the accelerating electrodes, also play a significant role.

The utilization of hydrogen as the accelerated gas should produce increased velocities in the motion of the plasma both through reduction of molecular weight and decreased loss through ionization.

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